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Abstract. The goals of the Mix Campaign were to determine how mix affects performance, locate the "mix cliff", locate the source of the mix, and develop mitigation methods that allow performance to be increased. We used several different drive pulse shapes and capsule designs in the Mix Campaign, to understand sensitivity to drive peak power, level of coast, rise time to peak power, adiabat, and dopant level in the capsule. Ablator material mixing into the hot spot has been shown conclusively with spectroscopy. The observed neutron yield drops steeply when the hot spot mix mass becomes too large. The mix appears to be driven by ablation-front Rayleigh-Taylor instabilities. A higher adiabat drive has allowed the mix mass in the hot spot to be reduced significantly. The two recent shots that achieved neutron yields > 10^{15} used the high-foot, high-adiabat drive. With the high-adiabat drive, YOC > 50% has been achieved, which was one of th goals of the Mix Campaign.

1 Introduction

The goal of inertial confinement fusion (ICF) is to compress deuterium (D) and tritium (T) to the densities and temperatures required to achieve a burst of D+T $\rightarrow$ ^{4}He+n+17.6 MeV fusion reactions of sufficient intensity that the energy output exceeds the energy input. The indirect drive approach pursued at the National Ignition Facility (NIF) uses a high power pulsed laser focused into a radiation cavity (hohlraum) to convert to soft x-rays which ablatively drive the implosion of a hollow spherical capsule at the center of the hohlraum. The capsule has a multi-layered ablator (Fig. 1a) and the radiation drive is shaped to launch 3-4 staged shocks to control the adiabat and achieve high compression of the fuel (Fig. 1b). [Haan 2011; Edwards 2013; Dittrich 2013] It has been known for decades, based on theory [Lindl 1975; Takabe 1985; Munro 1988; Haan 1989, 1990; Tabak 1990; Shvarts 1995; Betti 1996], 2D and 3D simulations [McCrory 1981; Verdon 1982; Sakagami 1990; Weber 1993; Marinak 1995; Hammel 2010; Clark 2011; Haan 2011] and experiments on high power lasers, [Wark 1986; Kilkenny 1990; Remington 1995; Budil 1996; Azechi 1997; Glendinning 2000; Smalyuk 2001, 2008; Cherfils 1999; Glendinnig 2000] that the capsule ablation front in ICF is unstable to the Rayleigh-Taylor (RT) instability and that the ablation process reduces RT growth rates. What is not known sufficiently are the detailed effects RT has on NIF capsule performance. This RT growth, if unchecked, could potentially become large enough to perturb the ablator-fuel and fuel-hot spot interfaces and ultimately lead to ablator material contaminating the hot spot and quenching the burn by radiative cooling, as indicated schematically in Fig. 2a. This mix failure mode is often referred to loosely as the "mix cliff", as suggested by the sketch in Fig. 2b. The goals of the Mix Campaign on NIF were to determine if such a mix cliff exists, locate it, determine how steep it is, and find ways to mitigate this mix failure mode. Once effective mitigation methods are found, the plan is to push the more robust capsules harder to test the limits of performance, and find the new mix cliff. Then this cycle of locating the mix cliff, finding new or more refined mix mitigation methods, then pushing these capsules to their new performance limits will be repeated, as we attempt to enter into the alpha heating ("boot strapping") regime, and push closer to ignition. The remainder of this article describes our progress in this endeavour; recent results are encouraging.

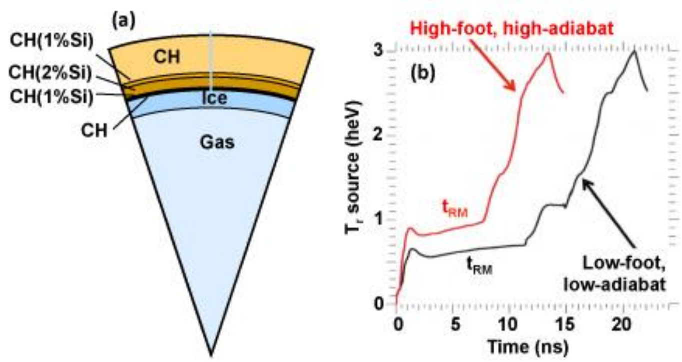

Figure 1. (a) Typical capsule used in NIF ignition experiments, corresponding to an outer radius of 1.15 mm. The layers, from the outside in, correspond to 138 μm of CH, 10 μm of CH(1% Si), 35 μm of CH(2% Si), 6 μm of CH(1% Si), 6 μm of CH, and 69 μm of cryogenic DT ice. (b) Drive radiation pulse shapes used for the 4-shock low-foot, low-adiabat drive (black curve) and the high-foot, high-adiabat drive (red curve).

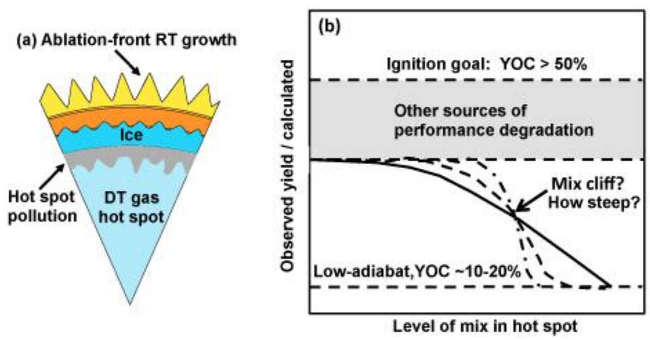

Figure 2. (a) This sketch illustrates the concern that large ablation-front Rayleigh-Taylor (RT) growth could sufficiently perturb the entire shell and fuel layer that CH ablator material can penetrate and pollute the DT hot spot. (b) The basic plan for the Mix Campaign is illustrated in this qualitative sketch. Our expectation at the onset of the Mix Campaign was that as the level of ablator mixed into the hot spot increases, the experimentally observed neutron yield compared to simulated (YOC) would decrease. Depending on the steepness, we called this the "mix cliff". For alpha heating and ignition, we need YOC > 50%.

2 Experiments to probe the mix cliff

The first conclusive experimental evidence that there was ablator material penetrating into the DT hot spot came from x-ray emission spectroscopy. In one "tri-doped" DT layered implosion, the innermost 6 μm ablator (adjust to the DT layer) had a 0.15% by number trace amount of Cu. And the next two layers moving back from the ice had 0.20% trace levels of Ge. In this implosion, Ge He-α emission from the hot spot was seen in the Supersnout-II spectrometer, but no Cu emission from the hot spot was observed, as shown in Fig. 3a. [Regan 2013] Both the Ge and Cu cold K-edges were observed in the surrounding shell. These experimental observations are consistent with the interpretation that ablation-front RT instability carries ablator material from the outside inward down into the hot spot, whereas instability growth at the ablator-fuel interface drives much less ablator into the hot spot. In parallel with these spectroscopy experiments, it was noticed that in poorly performing implosions, the neutron yield and ion temperature were low, but the hot spot x-ray emission was high. A very plausible way to explain this is that ablator material, in particular carbon, was mixed into the hot spot and radiatively cooled the hot spot, quenching the burn. This led to the development of the mix mass model, wherein the ratio of hot spot x-ray continuum yield to neutron yield can be fit with the one free parameter being the amount of ablator mixed into the hot spot. [Ma 2013] With this new mix mass model in hand, a full ensemble of cryogenic layered implosions can be plotted in terms of DT neutron yield vs experimentally inferred hot spot mix mass, as shown in Fig. 3b. It is quite clear from Fig. 3b that when the amount of ablator mixed down into the hot spot exceeds several hundred nanograms, neutron yield plummets sharply. The results shown in Fig. 3 all stem from the low-foot, low-adiabat drive shown in Fig. 1b, albeit with some variation in the rise time to peak power (1 ns, 2 ns, and 3 ns). At this point in the Mix Campaign, it was clear that we had located the "mix cliff", and that ablator mix into the hot spot was a strong failure mode that needed to be mitigated. The next section describes our initial work in mitigation.

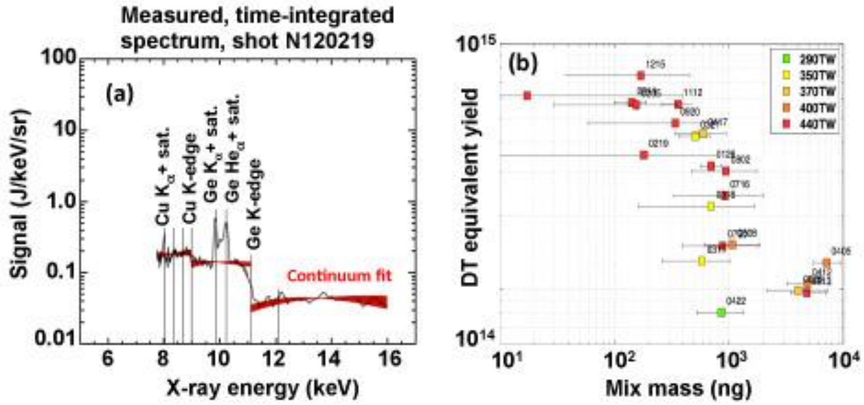

Fig. 3. (a) (a) Measured x-ray spectrum for an ignition target with a tri-doped ablator (black curve), corresponding to NIF shot N120219. The x-ray continuum from the hot spot transmitted through the compressed shell is modeled (red curve) assuming the x-ray continuum and the shell optical thickness scale with photon energy (hν) as exp(-hν/kT) and $(h\nu)^3$, respectively. [Regan 2013] (b) DT neutron yield versus inferred mix mass from the mix model for an ensemble of 21 cryogenic layered DT implosions on NIF. Points are color coded by peak laser power. [Ma 2013]

3 Mitigating Rayleigh-Taylor induced hot spot mix

There are several indications that ablation-front RT instability is one of the dominant causes of ablator material being mixed into the hot spot. First, as shown in Fig. 3a, the spectroscopy measurement on the tri-doped capsule showed strong Ge emission from the hot spot, but no emission from Cu. Second, when experimental mix mass is plotted versus experimentally inferred shell width (not shown), there is a trend that as shell width decreases, mix mass increases. Third, the experimental mix masses tend to increase when plotted against simulated ablation front growth factors (not shown). And finally, when mix masses are compared between the nominal capsules (Fig. 1a) and those with a factor of two increased silicon concentration, the latter had on average slightly higher mix mass (not shown). The above four observations are all consistent with ablation front RT being a dominant source of high ablator mix masses penetrating into the hot spot. Hence, our first mitigation strategy was aimed at a near-term modification that would reduce ablation-front RT growth. We maintained the same capsule shown in Fig. 1a, but switched to the high-foot, high-adiabat drive, shown by the red curve in Fig. 1b. Examples of the 2D design simulations comparing low-foot with high-foot are shown at peak compression in Fig. 4a. [Dittrich 2013] The high-foot design simulation converges slightly less, with convergence ratios (CR) of 25-30, as opposed to CR ~ 35-40 for the low-foot implosions. The high-foot simulation also shows less RT growth and spikes penetrating into the hot spot at this late stage of the implosion. When the ratio of experimental neutron yield over clean 1D simulation (YOC) is plotted, the high-foot implosions clearly demonstrate higher values, as shown in Fig. 4b. [Park 2013] Further, YOC for two of the shots surpassed the 50% threshold, which was one of the central goals of the Mix Campaign, as indicated in Fig. 2b. Further, analysis and simulations (not shown) demonstrated that shot N130812 in Fig. 4b produced 50% enhanced nuclear yield due to alpha heating, meaning these high-foot implosions are entering into the regime where alpha heating is starting to become significant. [Dittrich 2013; Park 2013] Alpha heating is the next goal being pursued in these mix mitigated high-foot implosions.

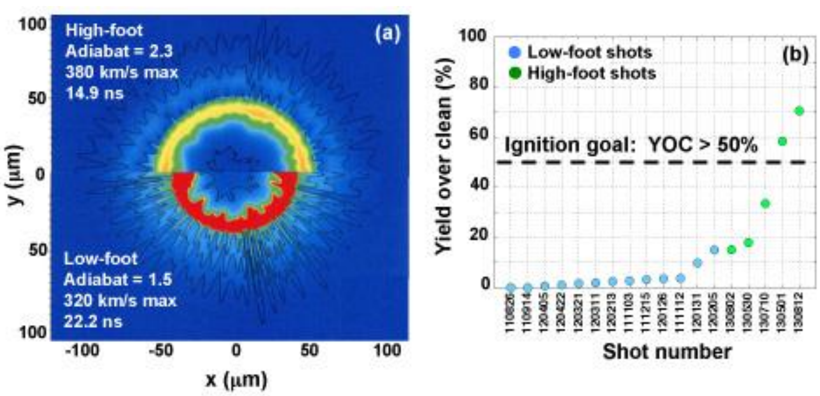

Fig. 4. (a) Two dimensional, 100-mode simulations with a spectrum of imposed surface roughness show, in density, the expected instability growth on the capsule. The bottom frame shows the low-foot capsule with adiabat α = 1.5 case and the top frame shows the high-foot, adiabat α = 2.3 case. The results are at the minimum implosion radius. [Dittrich 2013] (b) An ensemble of 18 cryogenic layered DT implosions plotted as experimental yield divided by clean 1D simulation. The blue symbols are for the low-foot, low-adiabat series and the green for the new high-foot, high-adiabat series.

4 Conclusion and future directions

In summary, the Mix Campaign conducted an extensive series of experiments. A steep mix cliff was found, using a number of diagnostic techniques. In particular, spectroscopy with tri-doped capsules, and the mix model based on comparing continuum x-ray yield to nuclear yield allowed the mix cliff to be mapped out, for the low-adiabat drives. Our mitigation strategy to date has focused on reducing ablation-front RT instability growth, using a higher adiabat design. This has allowed implosions with YOC > 50% and produced the first preliminary indications of the effects of alpha heating. This high YOC due to higher adiabat comes at the expense of reduced fuel areal density, however. Further work will test the limits of the high-foot design, and consider additional mitigation techniques, as we attempt to push performance further into the alpha heating regime.

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